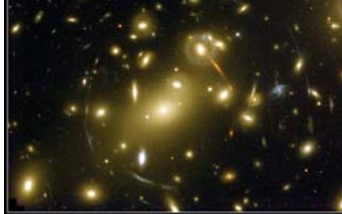

Galaxy Cluster Abell 2218
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC0

[Predicting] the number of gravitational arcs in clusters: redshift evolution and scaling of the cross section

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DARK ENERGY SURVEY

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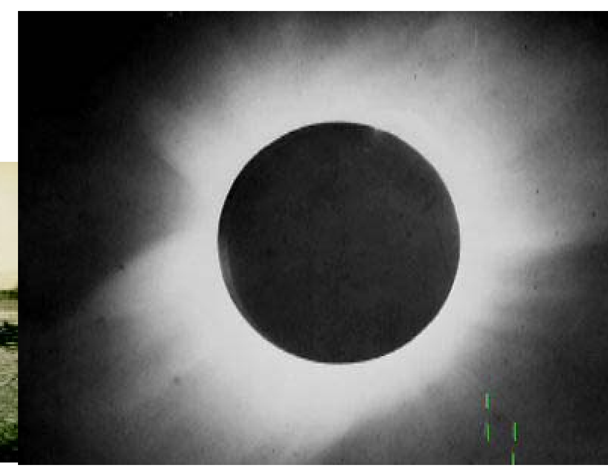
Motivation: Brief History of the Detection of the Light Deflection by Gravity

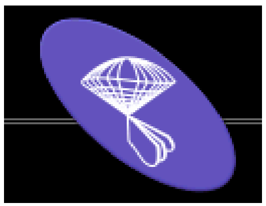
- 1912: Argentinean expedition to observe solar eclipse in Brazil
  - Got rained out
- 1914: Erwin Freundlich's expedition to observe an eclipse in Crimea (Russia)
  - Detained because WWI break up
- 1919: Sobral (Brazil)
  - Detection of the bending of light (better weather than Prince Island)



"The question that my mind formulated was answered by the sunny sky of Brazil"

Motivation

- Systematic arc search in SDSS clusters/imaging:
  - Vic Scarpine's poster (Estrada et al. 2007)
  - Efficiency of visual inspection and automated code
  - No arcs found!
- Apparent excess at high *z*
  - Dalal, Holder, Hennawi, et al.
  - EMSS, RCS, RCS2
- All the interesting physics you all know about
  - Lens structure
  - Cosmology
  - Etc.
- Upcoming wide field (deeper, better seeing) surveys
  - Dark Energy Survey



DARK ENERGY SURVEY

Observable: Giant Arc Abundance

- Average number of arcs per cluster (e.g. Horesh, Oguri)
- Why?
  - Relative distribution (Hennawi)
  - Does not depend on the mass function ("WMAP independent")
  - **Does not depend on the cluster selection method** (if not correlated with arcs…)
  - Does not need source redshift
- Goal: address *z* evolution with simple model

"**All** arc statistics computations are either wrong or incomplete"

Rocky Kolb

Expected number of arcs **per cluster**

- Number of arcs per cluster (pictorial)

$$N_{\text{arcos}} = \int \sigma(M, ..; z_S, z_L; R, \mu) N(z_S; m_{\lim}) f(R, m) \, dz_S \, d\mu \, dR$$

cross section for arc formation

source surface density

Selection function (detection efficiency)

Cross section in “Simulations”

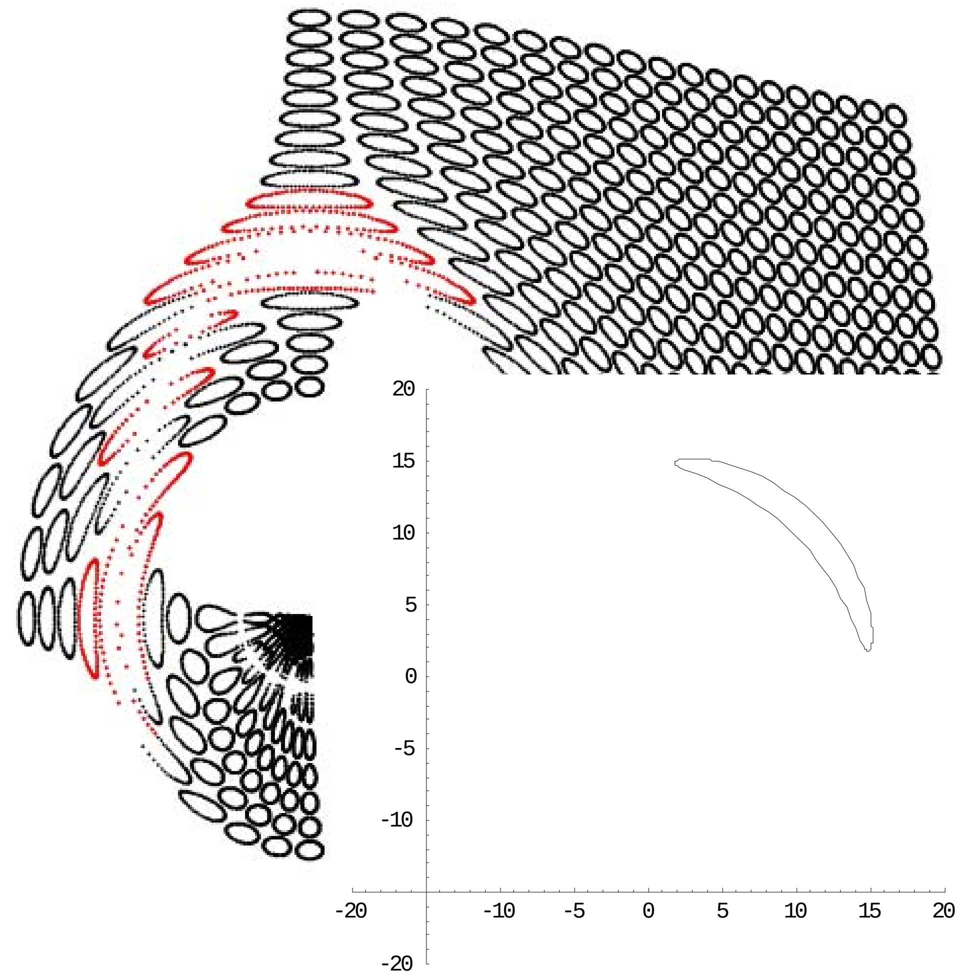
- NFW density profile

$$\rho = \frac{\rho_s}{\left(r/r_s\right)\left(1 + r/r_s\right)^2}$$

- Elliptical density distribution

$$r^2 = x^2 + \frac{y^2}{\left(1-e\right)^2}$$

- sources: ellipses
- **gravlens** modeling
- Image measurement
  - Algorithm based on analytic “arc function”



- Application of the cuts

"Local" cross section

- Eigenvalues of mapping

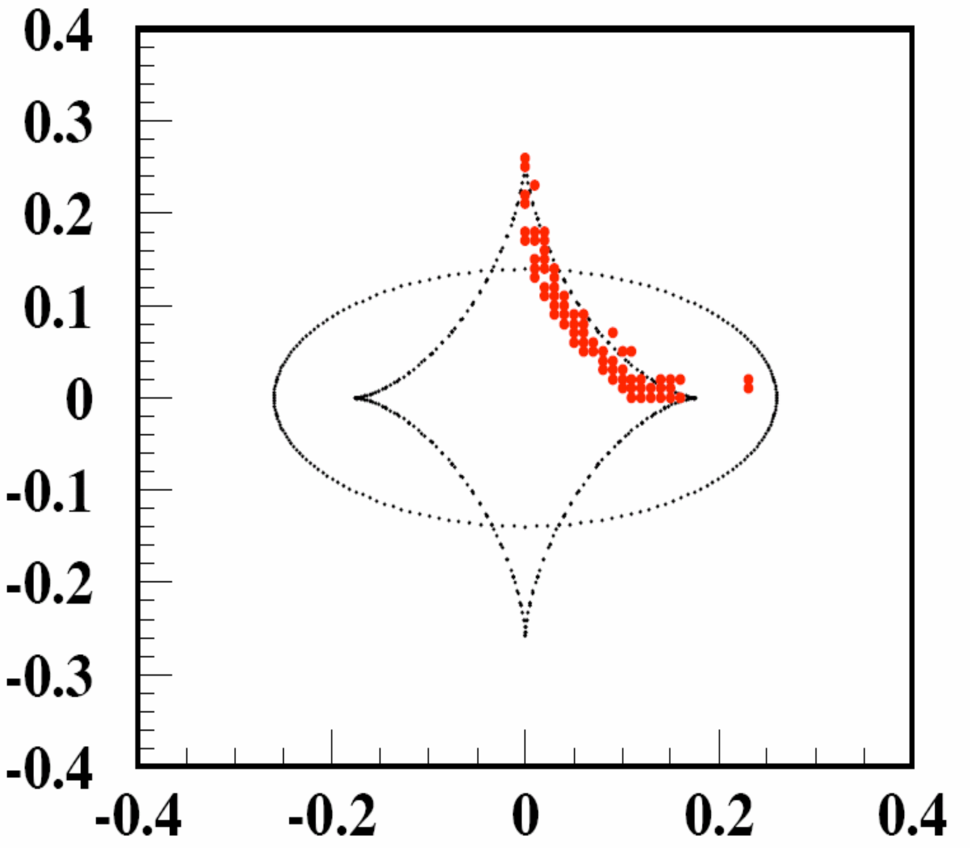
$$\mu_1 = \frac{1}{1-\kappa+\gamma}, \mu_2 = \frac{1}{1-\kappa-\gamma}$$

- Magnification and axial ratio

$$\mu = \mu_1\mu_2; \quad R = \frac{L}{W} = \max\left(\left|\frac{\mu_1}{\mu_2}\right|, \left|\frac{\mu_2}{\mu_1}\right|\right)$$

- Close to caustics
- Only tangential arcs

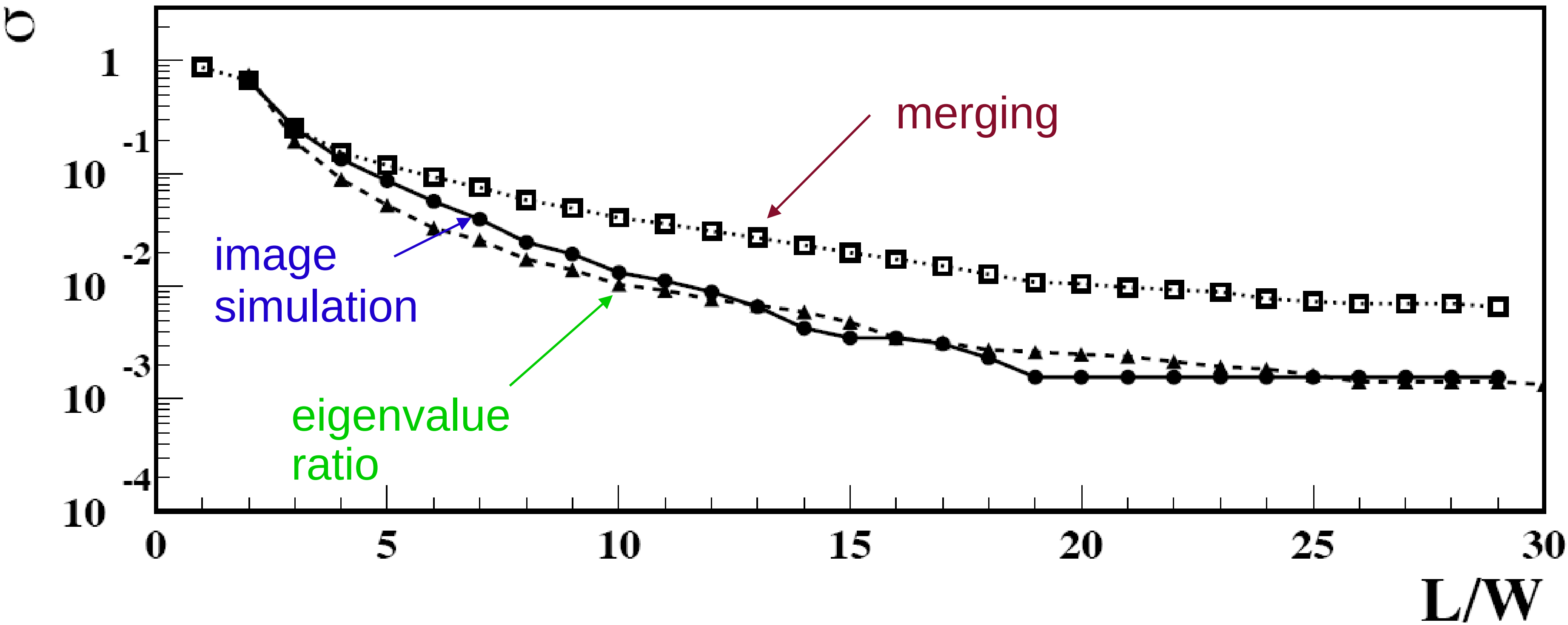
$$\sigma = \int_{\Omega(R>R_{th})} d^2\theta \frac{1}{\mu(\theta)}$$



- Much faster!

Local x Finite

- Eigenvalue ratio: good when there is no merging



- To simplify: proceed with eigenvalue ratio

NFW Cross Section

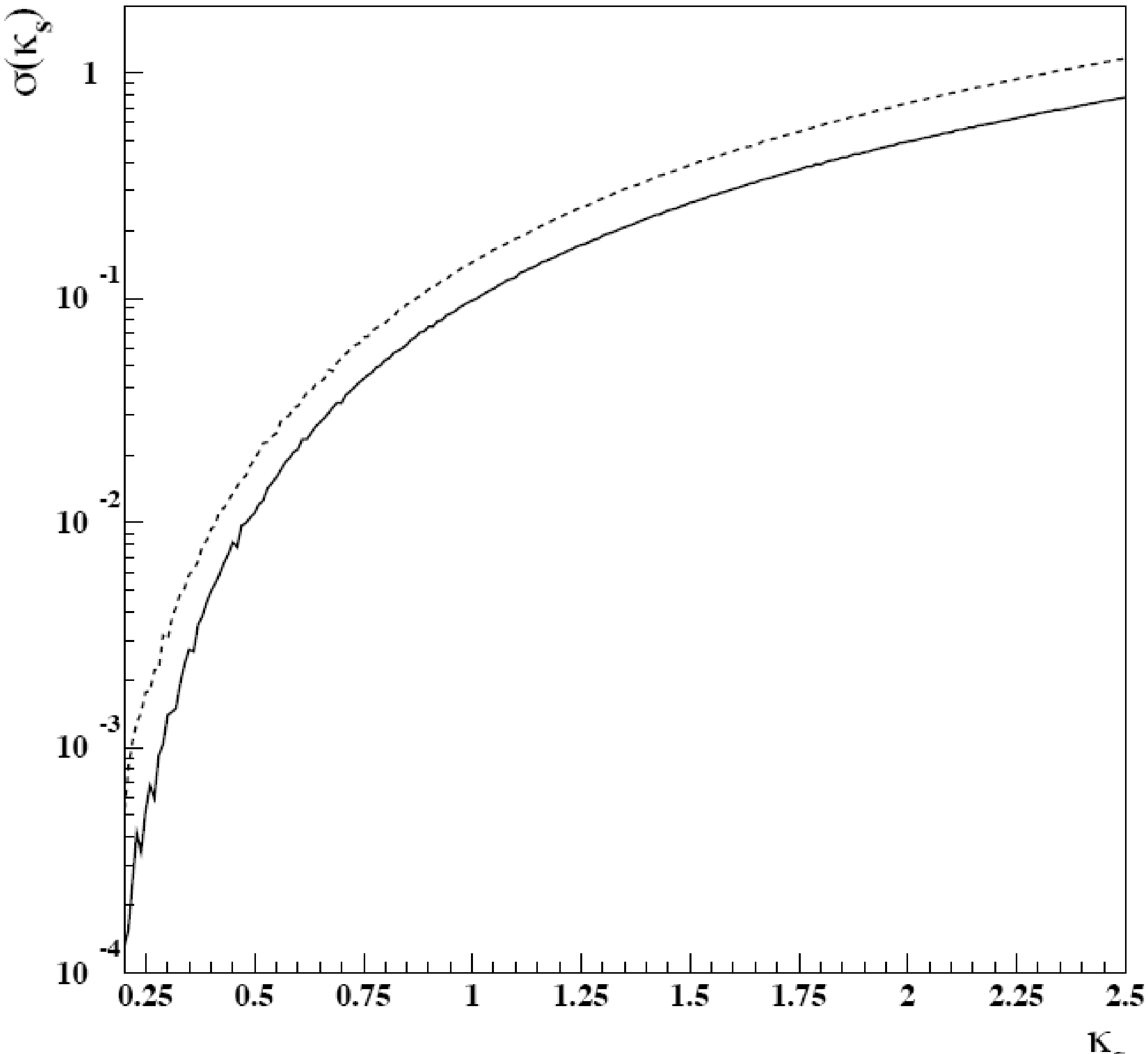
- Scaling with κ_s and r_s (Oguri et al. 2003):

$$\boxed{\sigma\left(M, c, e; z_L, z_S; R_{th}, \mu_{\lim}\right) = \tilde{\sigma}\left(k_s, e; R_{th}, \mu_{\lim}\right)\left(\frac{r_s}{D_L}\right)^2}$$

$$\kappa_s = 7.36 \times 10^{-4} \frac{c^2}{\ln(1+c) - c/(1+c)} \left(\Delta_{vir}\Omega_{M0}\right)^{2/3} (1+z)^2 E(z)^{2/3} \left(\frac{M_{vir}}{10^{14} M_\odot} h\right)^{1/3} \frac{I_{LS} I_{OL}}{I_{OS}},$$

Analogously for r_s

NFW Cross Section



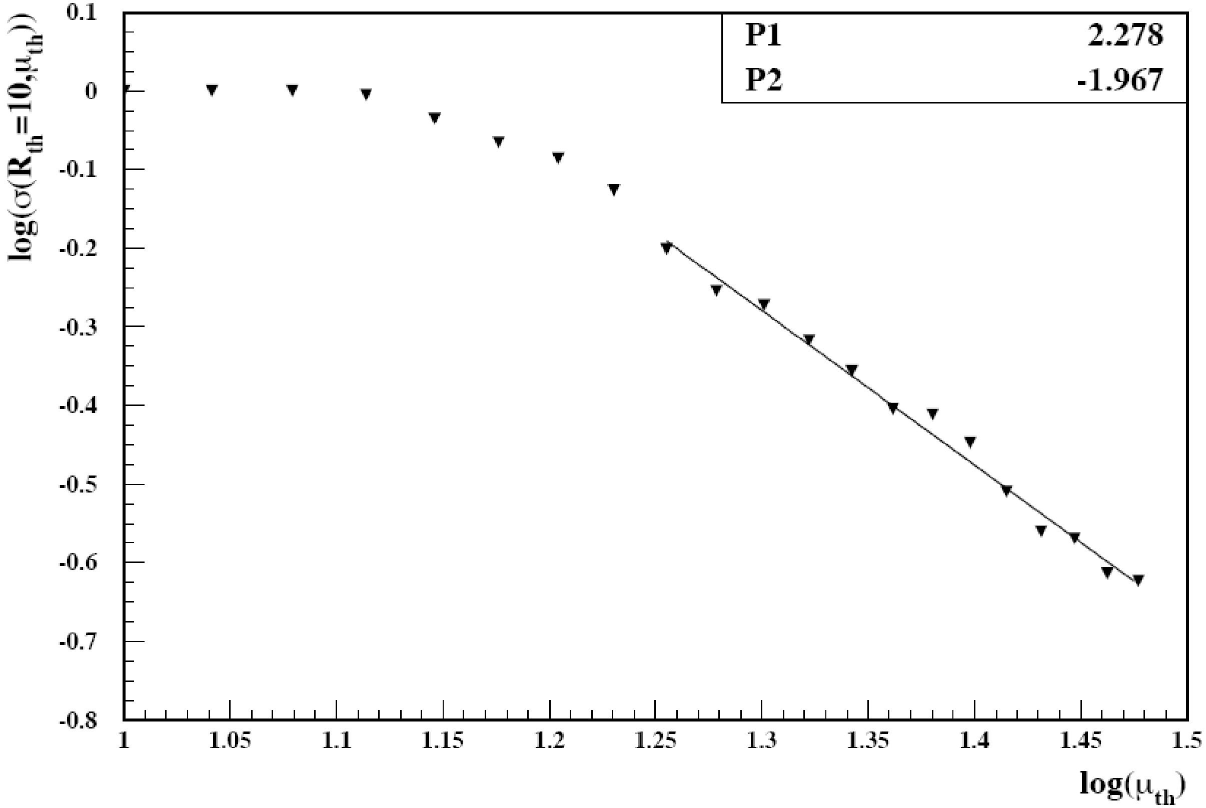
Nonlinear function of κ_s and hence of D_{eff}

Threshold effect

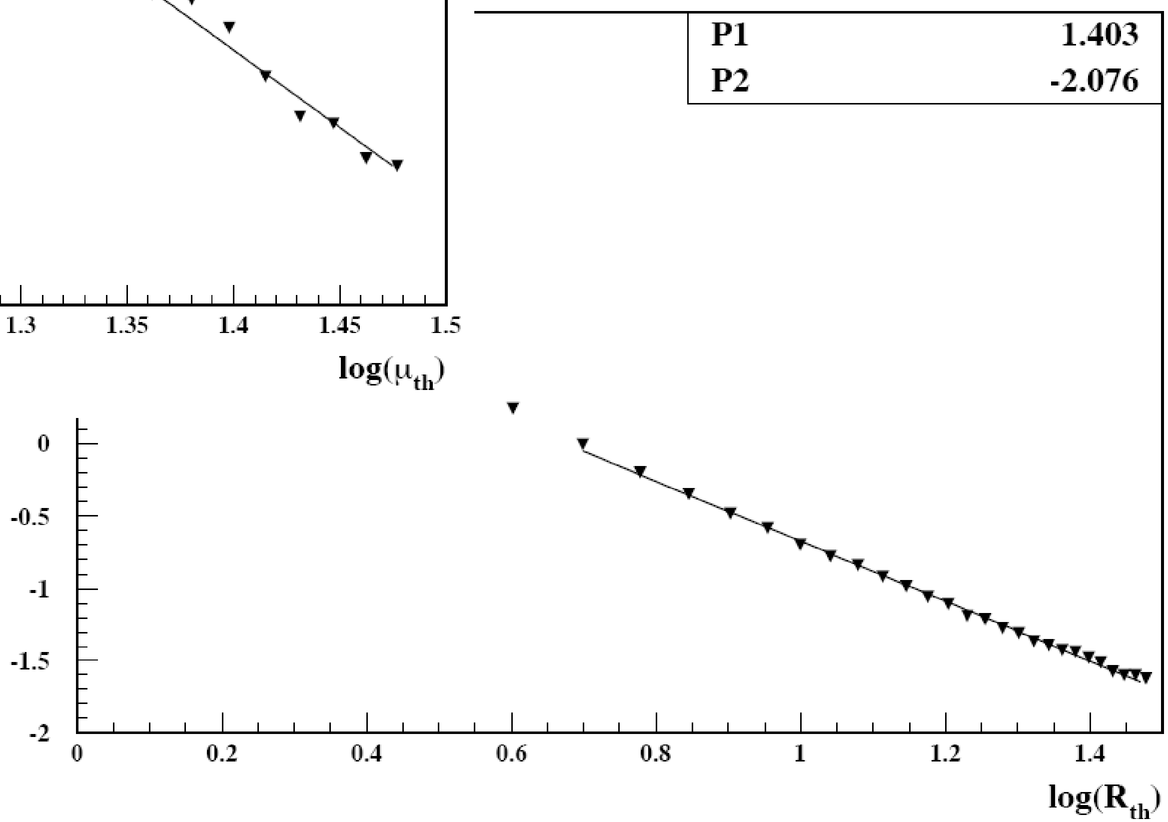
Scaling of the Cross Section

- Scaling with magnification **is** important:
  - grav. lensing conserves surface brightness
  - but there is noise! $S/N \propto \sqrt{A} \propto \sqrt{\mu}$
- Scaling with L/W **is** important:
  - seeing: $L' = \sqrt{L^2 + \theta_s{}^2}, \quad W' = \sqrt{W^2 + \theta_s{}^2}$
- Analytical results:
  - Close to folds: $\mu_T \propto \dfrac{1}{\sqrt{\beta - \beta_c}}$
  - Thus $\boxed{\sigma \propto \mu^{-2}, \ \sigma \propto R^{-2}}$

Scaling of the Cross Section



For fixed L/W ratio



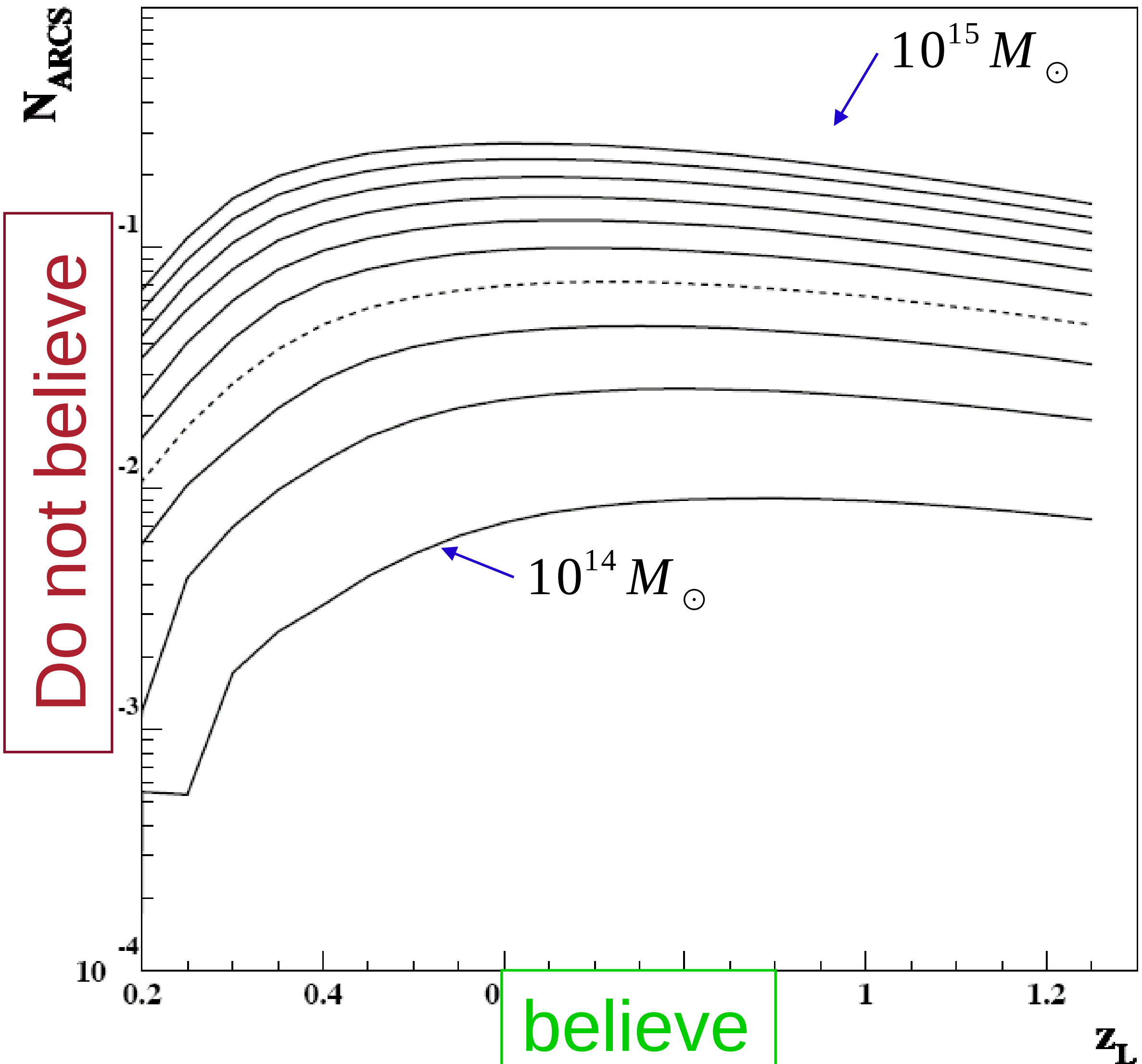
For any μ

Result

$$\frac{d\sigma\left(M, e; z_L, z_s; R_{th}, \mu_{th}\right)}{d\mu_{th}} = \tilde{\sigma}\left(\kappa_s, e\right)\left(\frac{r_s}{D_L}\right)^2\left(2\frac{\mu_{\min}{}^2}{\mu_{th}{}^3}\right)$$

$$N_{arcs} = \int\int \frac{d\sigma}{d\mu_{th}} n\left(z_S, m_{\lim} + 2.5\log\sqrt{\mu_{th}}\right) dz_S\, d\mu_{th}$$

Result



- Large variation with z
  - Threshold effect with *M*, *e*
- Connection to observed discrepancy?

Concluding Remarks

- Takes into account:
  - *N(z)*, detection efficiency, magnification
- Conjecture:
  - For single plane lensing
  - $\Rightarrow \exists$ "Universal cross section":

$$\boxed{\sigma\left(M, c, e\ldots; z_L, z_S; R_{th}, \mu_{\lim}\right) \propto \tilde{\sigma}\left(k_s, e, \ldots\right)\left(\frac{r_s}{D_L}\right)^2\left(\frac{\mu_{\min}^2}{\mu_{\lim}^2}\right)\left(\frac{1}{R_{th}^2}\right)}$$

  - Seen in numerical simulations (Rozo)
  - Can be generalized if cusps are important
- Use/test scalings with M, z_L, z_S, μ, R, etc. with simulated clusters